Visualizing Europa's Induced Magnetic Field

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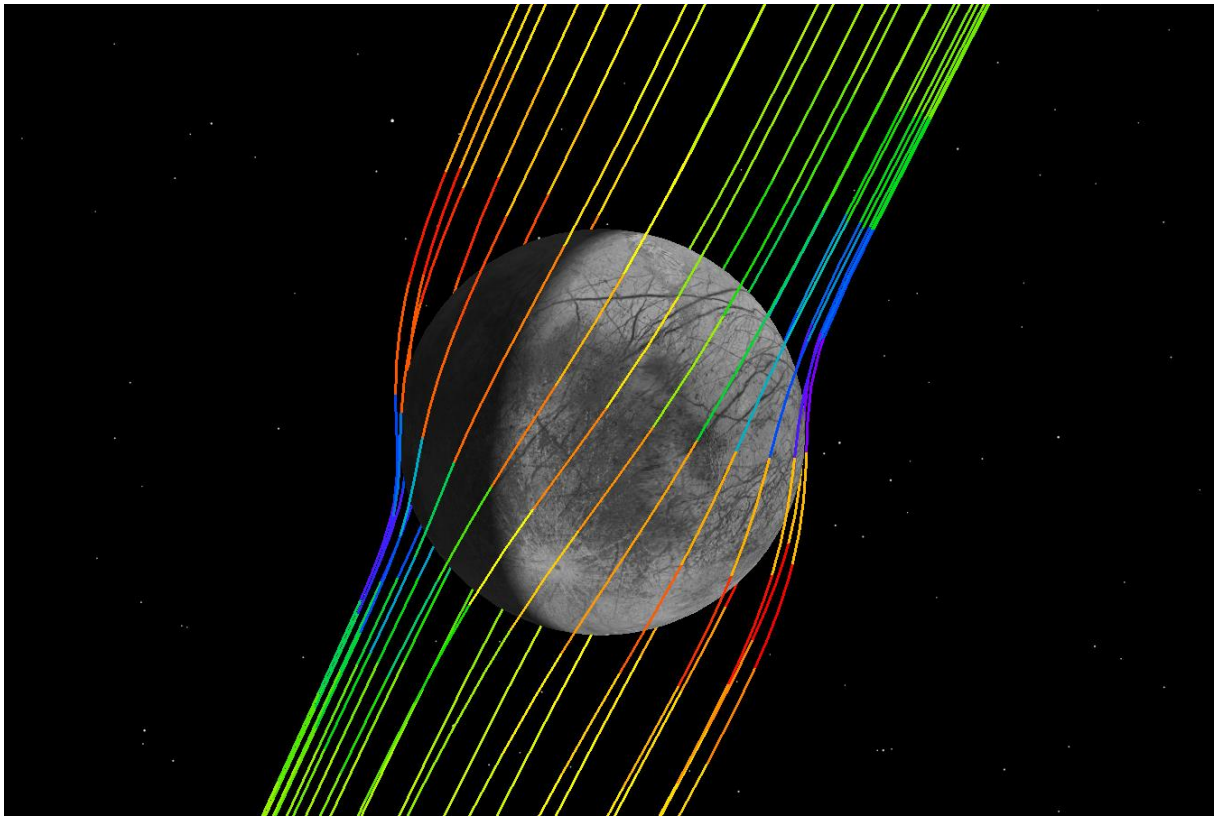

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Introduction

- Discovery of Europa's subsurface ocean via Europa's magnetic signature
  - M.G. Kivelson, et al., Europa's Magnetic Signature: Report from Galileo's Pass on Dec. 1996, *Science*, 276, (1997).
  - M.G. Kivelson, et al., "Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma env.", *J. Geophys. Res.*, 104, pp: 4609-4625, (1999).
  - M.G. Kivelson, et al., "Galileo Magnetometer Measurements: A stronger case for a subsurface Ocean at Europa", *Science*, 289, (2000).
- Much work in understanding, modeling, and visualizing Europa's induced magnetic field
  - X. Jia, M. Kivelson, K. Khurana, R. Walker, "Magnetic Fields of the Satellites of Jupiter and Saturn", *Space Sci Rev*, (2010) 152: 271–305.
  - K.K. Khurana, et al., Europa, *Electromagnetic Induction from Europa's Ocean and the Deep Interior, pp. 571-586, (2009).*
  - N. Schilling, et al., "Time-varying interaction of Europa with the Jovian magnetosphere", *Icarus*, 192, 41–55, (2007)
  - N. Schilling, et al., "Limits on an intrinsic dipole moment in Europa" *J. Geophys. Res., 109, E5, 2004.*
  - K.K. Khurana, et al., "Searching for Liquid Water in Europa by Using Surface Observatories", *Astrobiology*, 2, 1, pp: 93-103 (2002).
  - C. Zimmer, at al., "Subsurface Oceans on Europa and Callisto: Constraints from Galileo Magnetometer Observations", *Icarus*, 147, 329–347 (2000).
- JPL (Erick Sturm and others) has been involved in developing software for visualizing Jupiter's magnetic field called Jupiter Environment Tool (JET)
  - However, no initial plan for developing a visualization for Europa's induced field due to it's complexity.
- Partial role as an Investigation Scientist …
  - keep the software alive, maintained, and progressing
  - look for additional options which would allow non-windows users to leverage the software
- Erick did much of his own software maintenance, motivated me to …
  - Implement an induced dipole magnetic field model for Europa in JET/STK
  - Investigate alternative programming environments for visualizations (Matlab/SPICE)

Outline

- Introduction to software platforms
  - Jupiter Environment Tool (JET)
  - SPICE Toolkit
- Background necessary for understanding Europa's Induced Magnetic Field
  - The Origin of a Magnetic Field
  - Difficulties in visualizing Europa's magnetic field
  - VIP4 Magnetic Field Model of Jupiter
  - Jupiter's Time Varying Magnetic Field at Europa
  - Concept of Magnetic Induction
- Extracting magnetic waves at various frequencies
  - Frequency Content of Jupiter's time varying magnetic field
  - Extracting 11 hour and 85 hour magnetic field components
- MATLAB simulations (with the aid of Mice)
  - Drawing Magnetic Field Lines
  - 11 hour and 85 hour dipole simulations
  - Total magnetic field simulation
- JET/STK simulations
  - GUI interface
  - 11 hour and 85 hour dipole simulations
  - Total magnetic field simulation
- Applicability to Europa Clipper Mission
  - Magnetic field experienced by Clipper along the 17F12v2 trajectory
  - Clipper flyby

JET Plugin for STK

- What is the Jupiter Environment Tool (JET)?
  - Custom GUI plugin for STK for visualizing Jupiter's (and others) magnetic fields and radiation environment
- What is Systems Tool Kit (STK)? (formerly Satellite Tool Kit)
  - It is a physics-based software package from Analytical Graphics, Inc. that allows engineers and scientists to perform complex analyses of ground, sea, air, and space assets.
- How did it begin?
  - Was a desire for an analog of Space Environment and Space Tool (SEET) for Earth.
    - Visualization of the magnetosphere, Radiation fields, Plasma and neutral Tori, Rings/dust/small bodies, Satellite atmospheres
  - Erick Sturm, a few interns and other JPL employees began the work in 2010.
- Current Capabilities (for more information: https://solarsystem.nasa.gov/europa/jet.cfm)
  - Jupiter system
    - Jupiter magnetic field: dipole, Voyager Io Footprint Pioneer (VIP4)
    - Jupiter plasma: Galileo Interim Radiation Electron (GIRE1, GIRE2)
    - Ganymede magnetic field: dipole
    - No Europa!
  - Other bodies: Saturn, Uranus
- Limitations
  - STK can be only installed on PC
  - Not so straight forward to make programs without understanding the entire workings of JET and STK

SPICE toolkit

- What is SPICE? - Spacecraft, Planet, Instrument, C-orientation, Events
  - Library of subroutines that are able to read the kernel files and calculate observation geometry parameters of interest to scientists and engineers —range, LAT/LON, and lighting angles.

- How did it begin?
  - NASA's Navigation and Ancillary Information Facility (NAIF) was established at the Jet Propulsion Laboratory to lead the design and implementation of the "SPICE" ancillary information system.

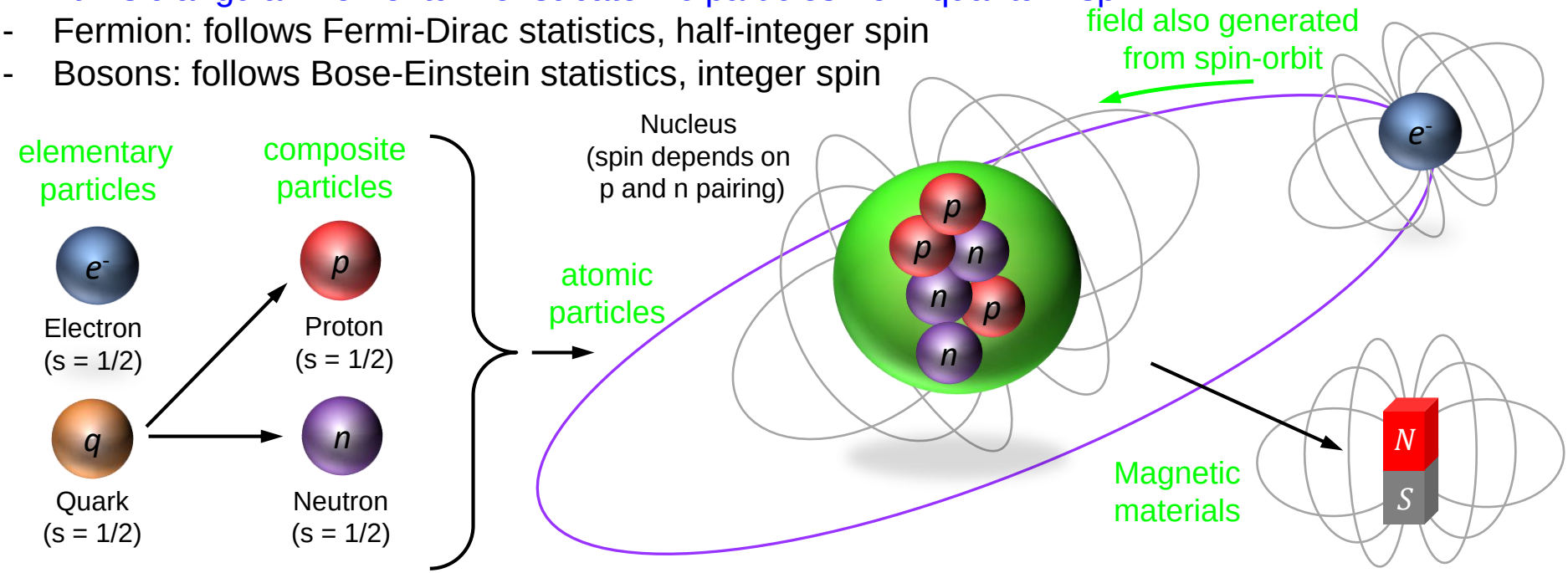
- Applicable environments
  - Routines can be used in C, Fortran, IDL, MATLAB

- Advantages over JET/STK
  - Can be used on any operating system (e.g. windows, mac, linux)
  - 4 programming languages available makes it easy for anyone to write their own custom programs
  - Easier to write complex signal processing schemes necessary for visualizing Europa's magnetic field due to libraries available in other programming environments.

From Subatomic to Planetary …

Origin of Magnetic Fields

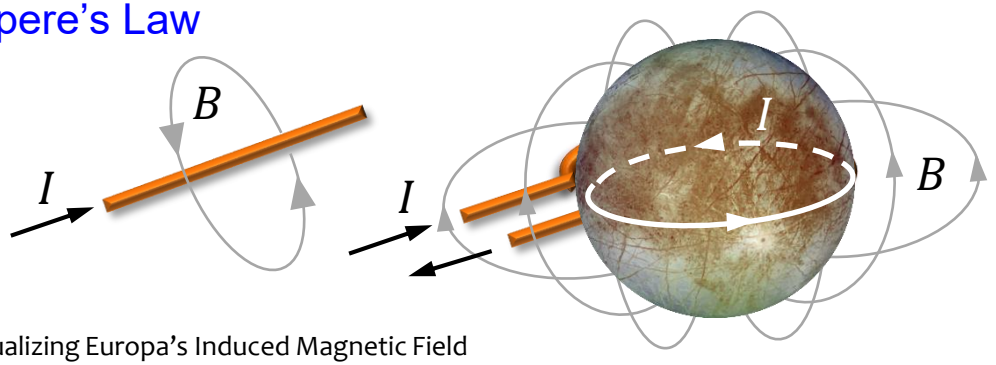
1. Intrinsic angular momentum of subatomic particles from quantum spin:
- Fermion: follows Fermi-Dirac statistics, half-integer spin
- Bosons: follows Bose-Einstein statistics, integer spin



2. Moving electric charge as described by Ampere's Law

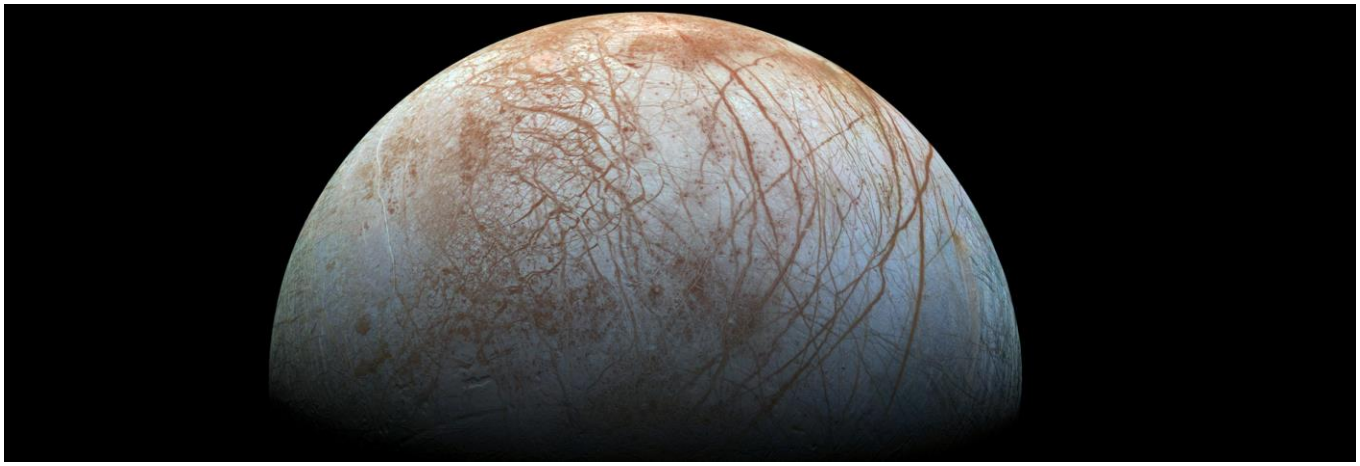
$$\oint B \cdot dl = \mu_0 \iint_S J \cdot ds = \mu_0 I$$

Integrated magnetic field along a closed loop is proportional to the current passing through that surface



Difficulties in Visualizing Europa's Field

- No internal self-sustaining dynamo and therefore field does not depend on geographic location
- Depends on Jupiter's magnetic field
  - Need model of Jupiter's magnetic field to estimate
  - Jupiter's magnetic field at Europa is time dependent
  - Europa's field is induced, and therefore only depends on the changing magnetic field
  - Oscillating magnetic field components are dominated by strong constant –z component
  - There are many time varying components (multiple frequencies) in the Jupiter/Europa system … some are more dominant than others.
  - Orientation and magnitude for each magnetic wave is also time-varying.



VIP4 Magnetic Field Model of Jupiter

Jupiter's Magnetic Field

- Internal Component: generated by currents in outer core, composed of liquid metallic hydrogen which behaves like an electrical conductor
- External Component: due to azimuthal ring current which flows within the equatorial plasma sheet which corotates with the planet
- VIP4: Voyager Io-Footprint Pioneer 4 (indicative of the spherical harmonic order)
  - Current sheet
    - half-thickness = 2.5 R_J, from 5R_J to 50R_J
    - Colatitude: $\theta = 9.52°$, Longitude: $\phi = 158°$
    - Current constant: 0.0045 Gauss

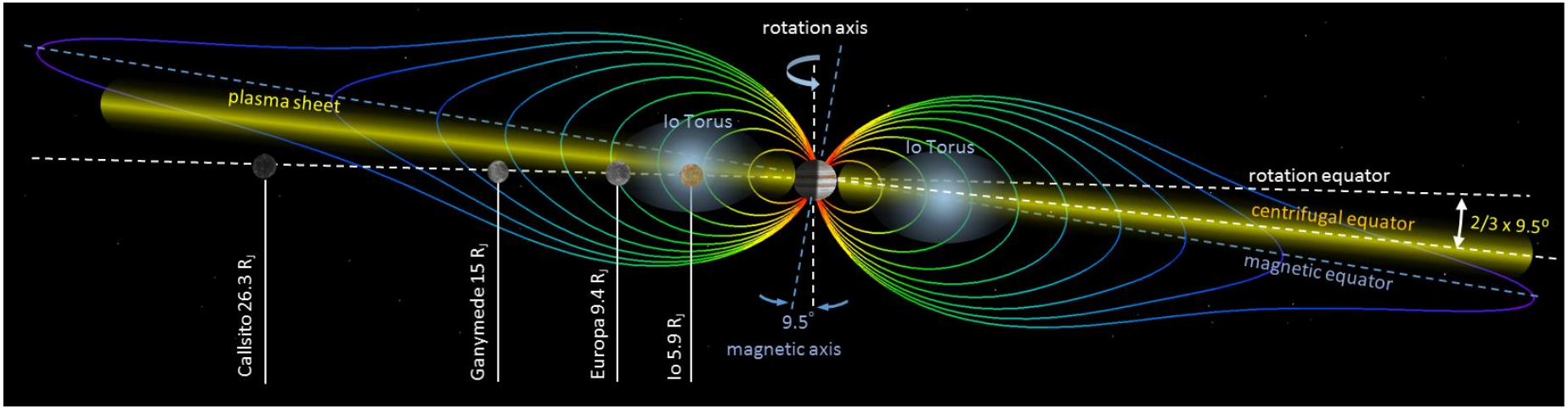
$$B = -\nabla V + b$$

$B = magnetic\ field, V = magnetic\ scalar\ potential,$
$b = perturbation\ field\ due\ to\ external\ currents$

$$V = R \sum_{n=1}^{n_{max}} \left(\frac{R}{r}\right)^{n+1} \sum_{m=0}^{n} \{P_n{}^m(cos\theta)[g_n{}^m \cos(m\phi) + h_n{}^m \sin(m\phi)]\}$$

$R = equitorial\ radius\ of\ Jupiter, \quad r\ is\ radial\ distance\ to\ center$
$\theta = colatitude, \phi = longitude$
$P_n{}^m(cos\theta) = Schmidt\ seminormalized\ Legrendre\ functions$
$g_n{}^m, h_n{}^m = internal\ \ Schmidt\ coefficients$

Connerney, Acuna, et. al, Journal of Geophysical Research, vol. 103, no. A6, pp. 11,929-11,939, June 1, 1998.

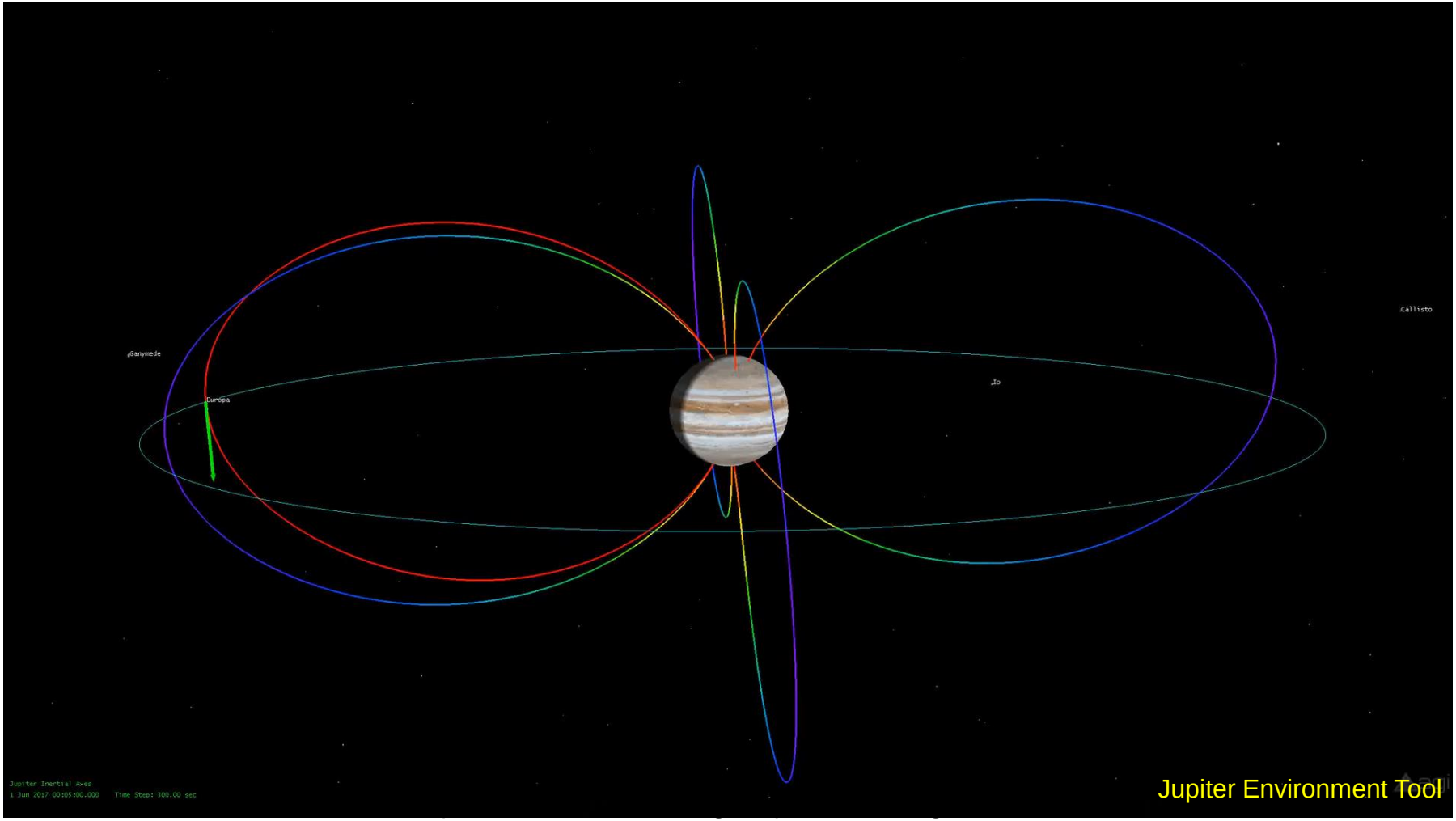


Europa Science Series – Visualizing Europa's Induced Magnetic Field

Jupiter's Time Varying Magnetic Field at Europa

Jupiter's magnetic field is dipole-like at the orbit of Europa and is time varying due to

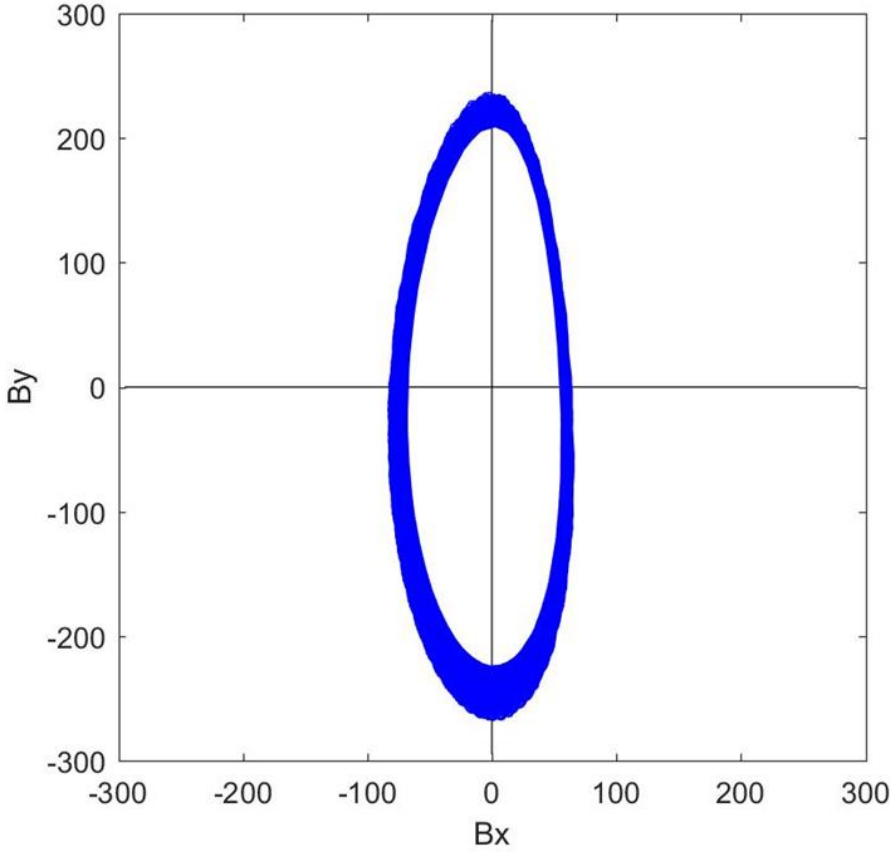
1. Jupiter's magnetic axis is offset by 9.5º with to its spin axis (11hr period)
2. Europa's slight eccentric orbit and inclination about Jupiter (85 hr period)

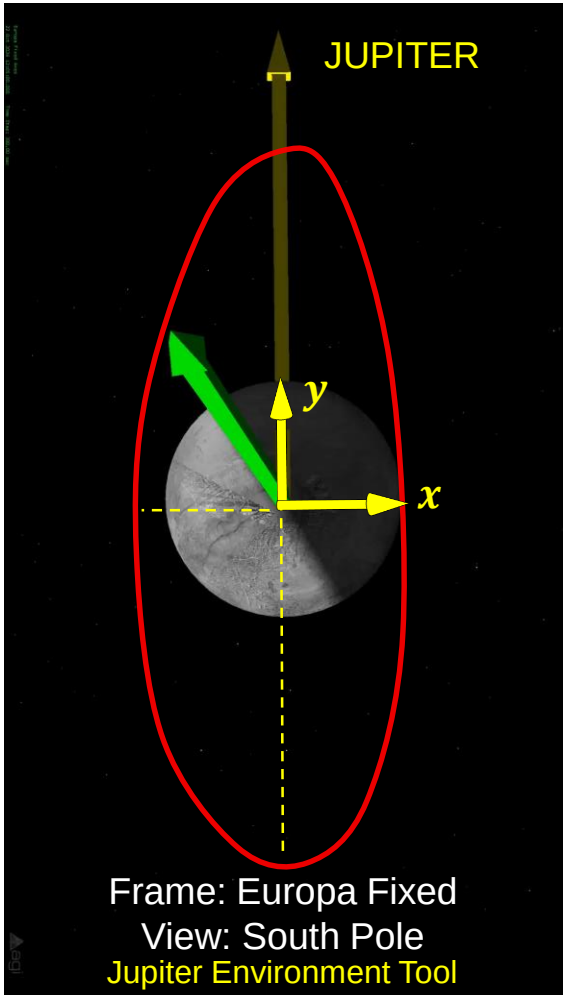


Jupiter's Time Varying Magnetic Field at Europa

In the IAU_EUROPA reference frame (synchronous orbit around Jupiter),

- x and y components of the magnetic field are time varying
- period consistent with Jupiter's rotation (11 hour)

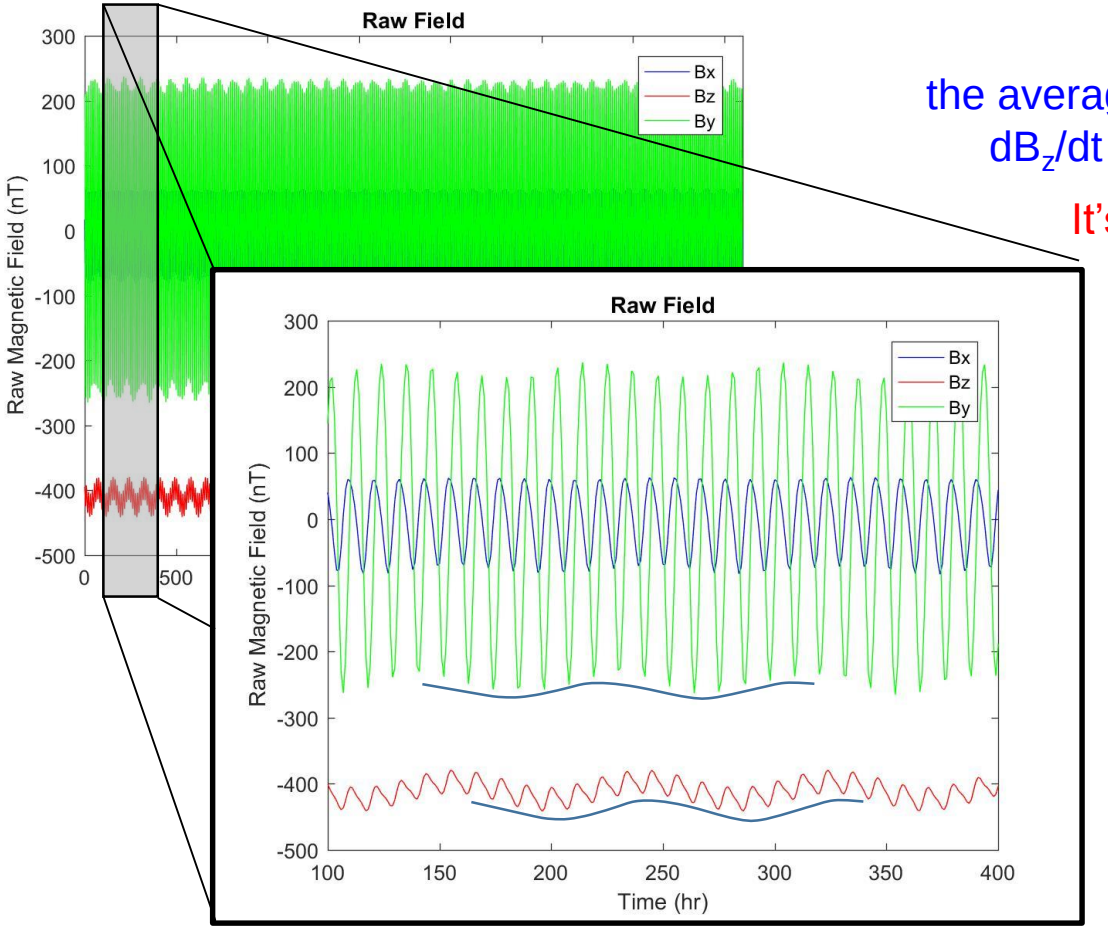




Jupiter's Time Varying Magnetic Field at Europa

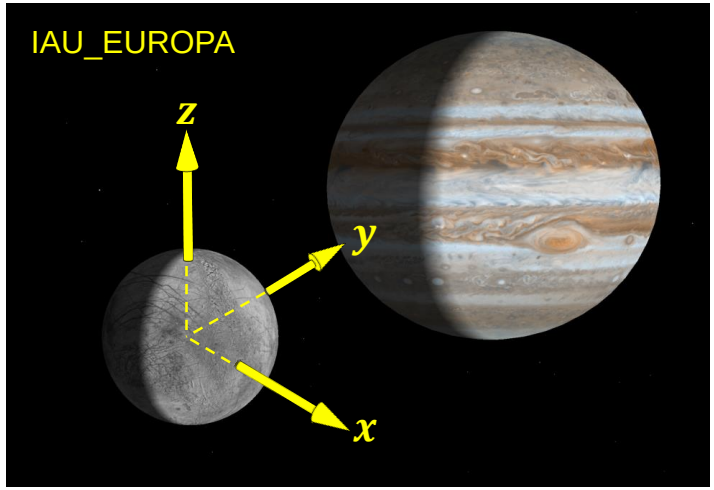
- In the IAU_EUROPA reference frame (synchronous orbit around Jupiter), Europa experience a time-varying magnetic field for all x, y, and z components.

- Data below is indicative of VIP4 model components evaluated at orbit of Europa.



the average of B_z is large, but small for B_x and B_y
dB_z/dt is small, dB_y/dt and dB_x/dt are large

It's the time varying components that matter, but why?



What is Magnetic Induction?

Europa's induced magnetic field can be understood by the conductive coil in the presence of a moving bar magnetic analogy

Faraday's Law: $\nabla \times \boldsymbol{E} = -\frac{d\boldsymbol{B}}{dt}$

Lenz's Law: The direction of current induced in a conductor by a changing magnetic field due to induction is such that it creates a magnetic field that opposes the change that produced it.

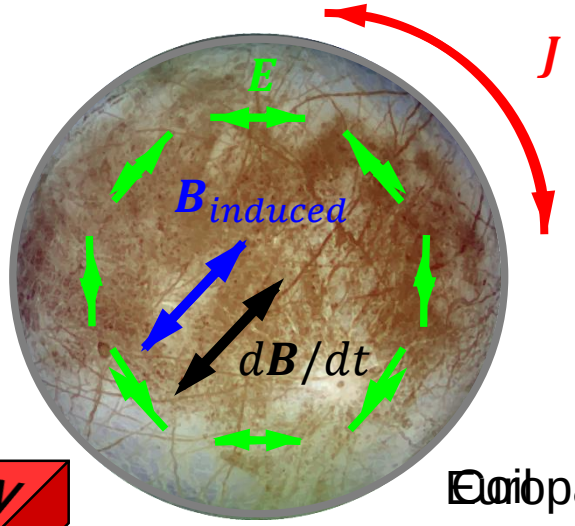
Moving magnetic field causes current to flow within Europa's conductive ocean which induces a magnetic field that opposes the original field

Stationary magnet does not induce a field because dB/dt = 0

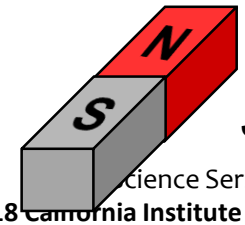
Also depends on …
Ampere's Law: $\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}$
Ohm's Law: $\boldsymbol{J} = \sigma \boldsymbol{E}$

Which leads to the….
Diffusion Equation: $\nabla^2 \boldsymbol{B} = \mu_0 \sigma \frac{d\boldsymbol{B}}{dt}$

$\mu_0 = premeability$
$\sigma = conductivity$
$\nabla = \frac{d}{dx} i + \frac{d}{dy} j + \frac{d}{dz} k$



More complicated due to driving field in three dimensions and at multiple frequencies.



Bar Magnet

Europa

Jupiter's Time Varying Magnetic Field

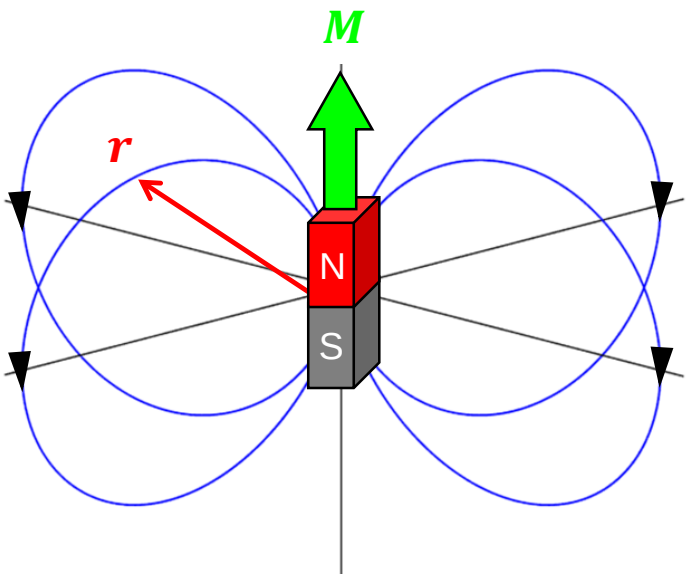
Europa's Induced Dipole Magnetic Field

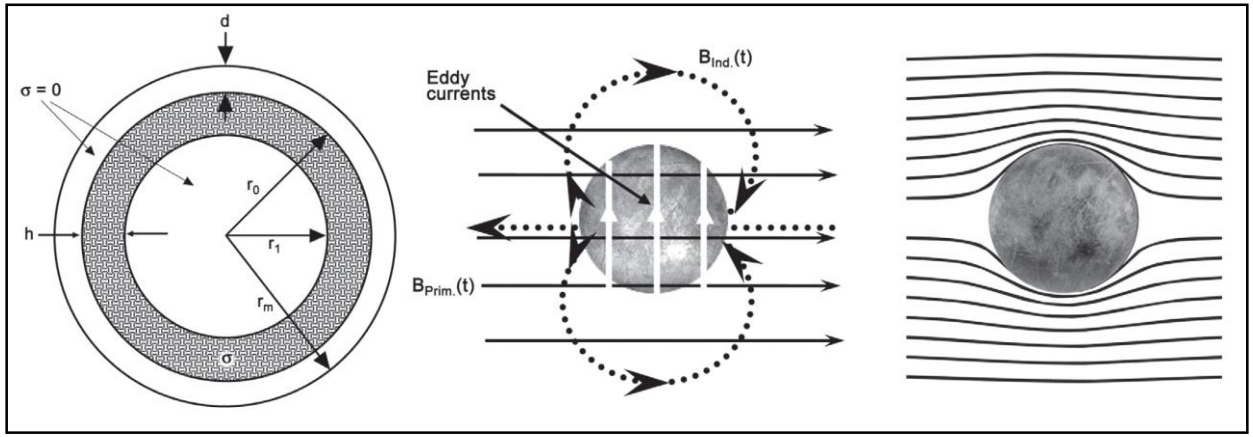
- Three shell model: insulating ice shell, spherical conductive ocean, and insulating core
- Dipole moment of the induced field oscillates at the same frequency but opposite direction of the primary field and is phase delayed

$$\boldsymbol{M}_{ind} = -\frac{4\pi}{\mu_0} A e^{i\emptyset} \frac{\boldsymbol{B}_{prim} r_m^3}{2}$$

$$\boldsymbol{B}_{ind} = \frac{\mu_0}{4\pi} \frac{3(\boldsymbol{r}\cdot\boldsymbol{M})\boldsymbol{r} - r^2\boldsymbol{M}}{r^5}$$

$\boldsymbol{M}_{ind} = induced\ magnetic\ moment$
$\boldsymbol{B}_{ind} = induced\ magnetic\ field$
$\boldsymbol{r} = radial\ distance$
$\mu_0 = \ permeability$
$A = relative\ amplitude\ (A = 1)$
$\emptyset = phase\ lag\ (\emptyset = 0)$





$$\boldsymbol{M} = \hat{x}M_x + \hat{y}M_y + \hat{z}M_z$$

$$B_x = \frac{\mu_o}{4\pi r^3}\left[\frac{3(M_x r_x + M_y r_y + M_z r_z)r_x}{r^2} - M_x\right]$$

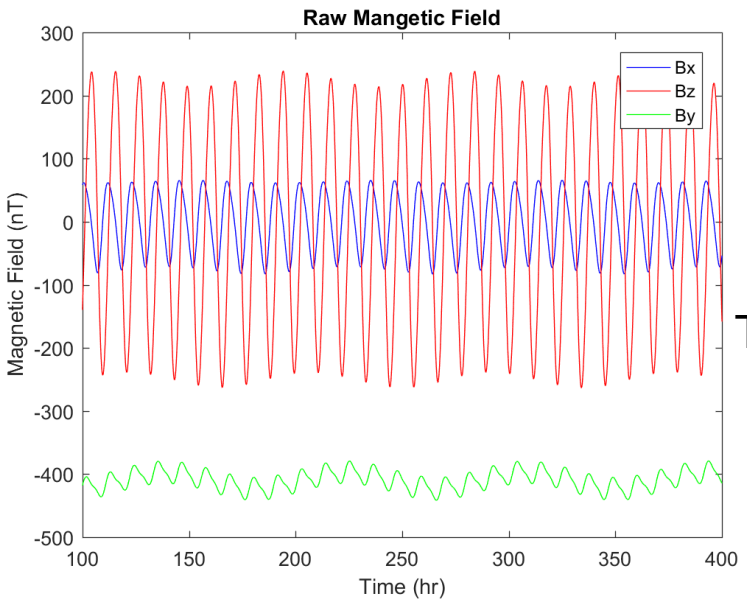
$$B_y = \frac{\mu_o}{4\pi r^3}\left[\frac{3(M_x r_x + M_y r_y + M_z r_z)r_y}{r^2} - M_y\right]$$

$$B_z = \frac{\mu_o}{4\pi r^3}\left[\frac{3(M_x r_x + M_y r_y + M_z r_z)r_z}{r^2} - M_z\right]$$

C. Zimmer, at al., "Subsurface Oceans on Europa and Callisto: Constraints from Galileo Magnetometer Observations", *Icarus*, 147, 329–347 (2000).
K. Khurana, M. Kivelson, et al., Europa, *Electromagnetic Induction from Europa's Ocean and the Deep Interior, pp. 571-586, 2009.*

Frequency Content of Time Varying Field

Taking the Fourier transform reveals not only the 11 hr and 85 hr periods, but also the higher order harmonic and beat frequencies associated with the time varying magnetic field of Jupiter.

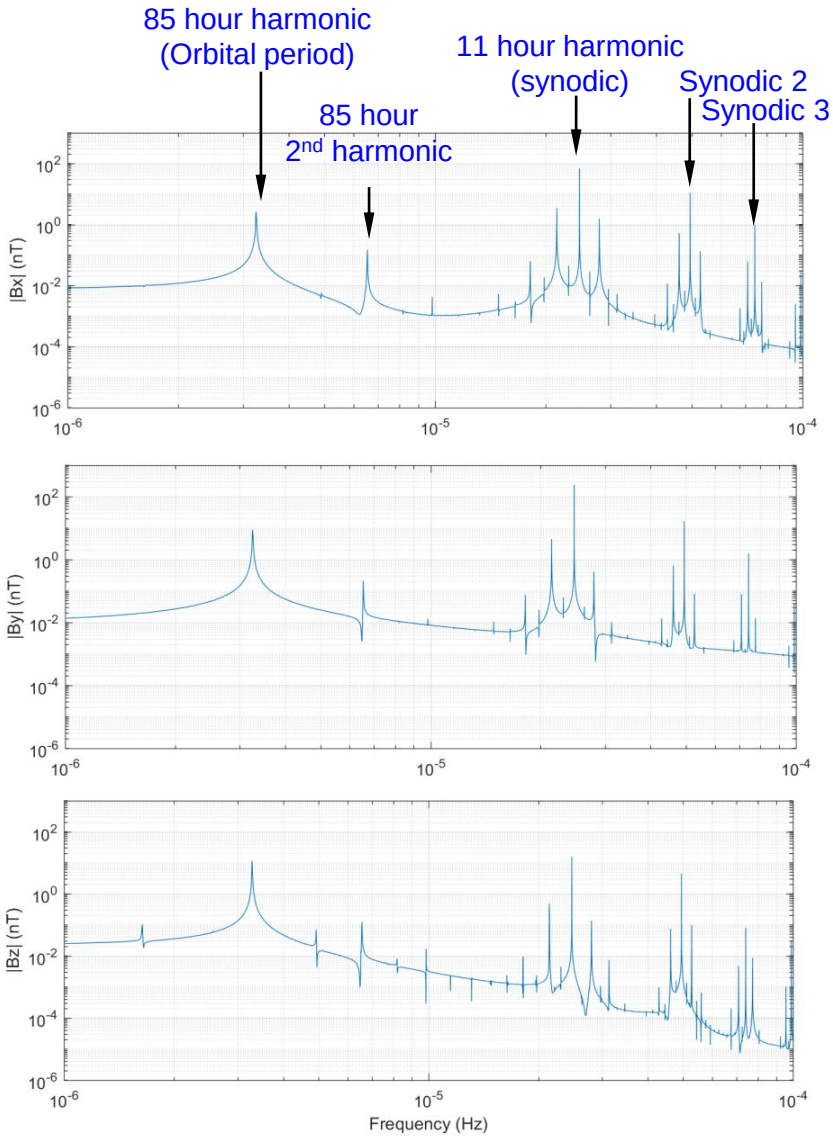


X

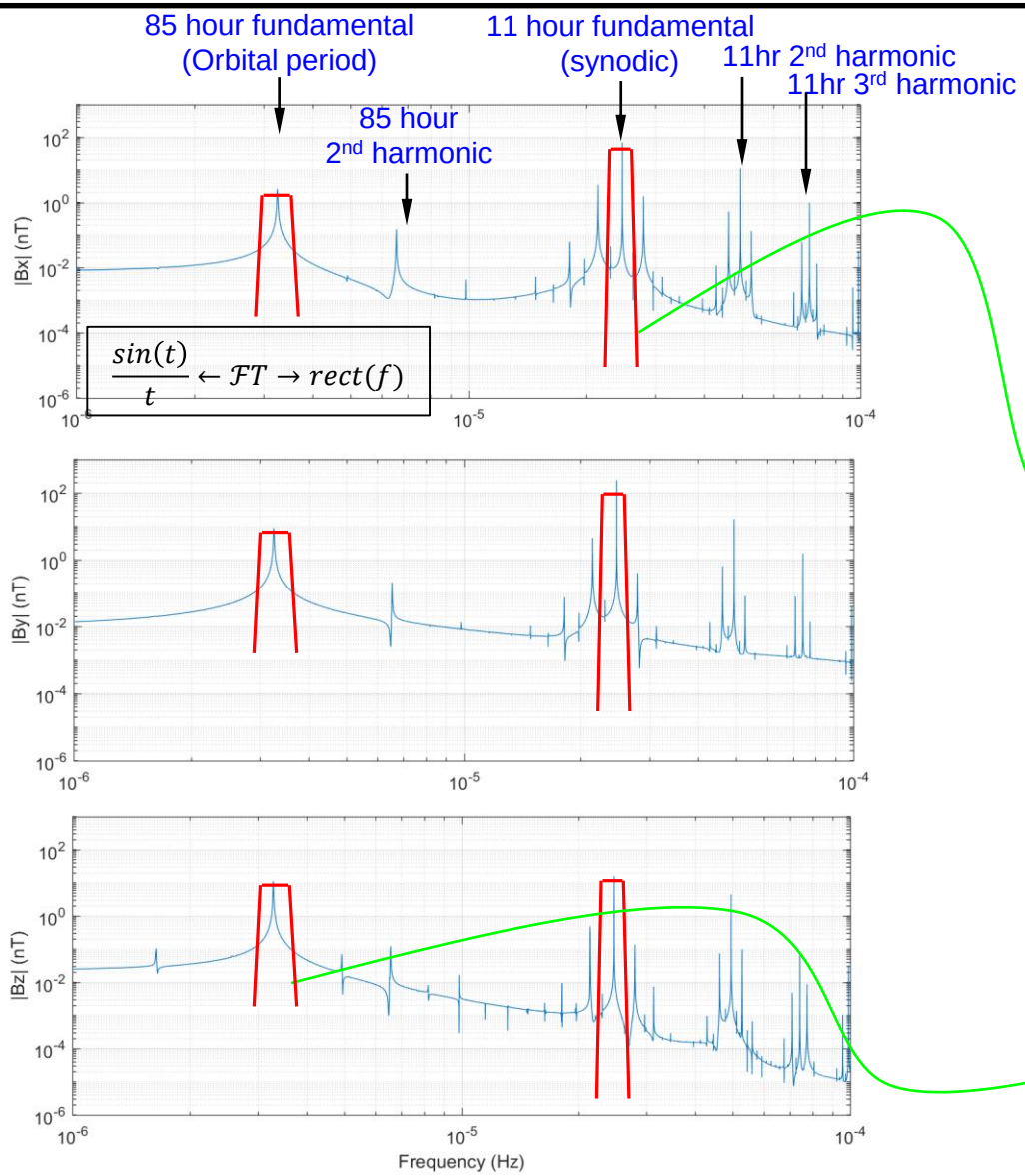
Y

Fourier Transform

Z

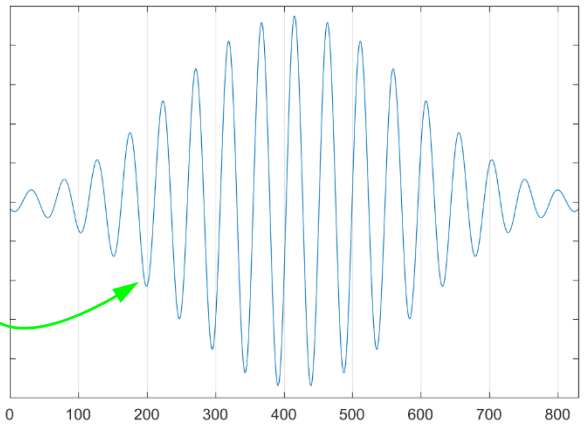


Extracting 11hr and 85 hr components

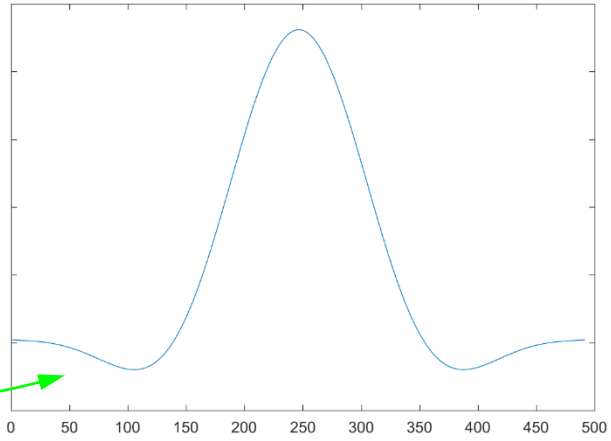


FIR 11 hr and 85 hr FIR Filters

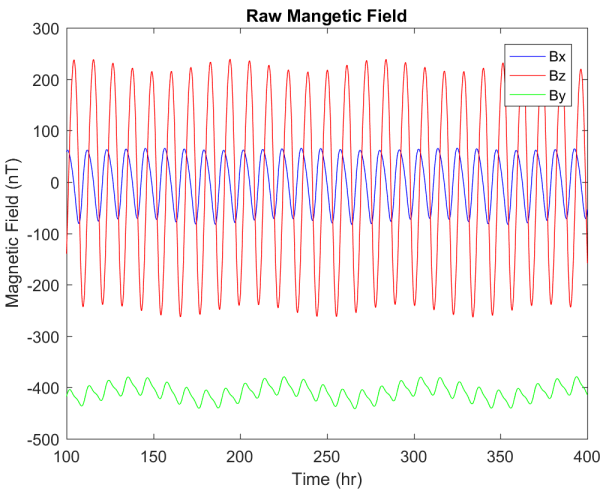
11hr components dependent of convolution of waveform with time domain series



85hr components dependent of convolution of waveform with time domain series



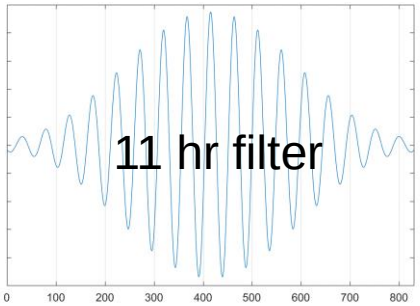
Extracting 11hr and 85hr components

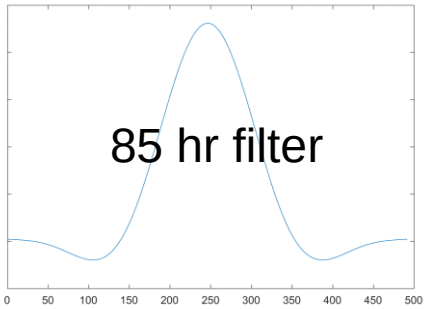


$\boldsymbol{B}(t)$

convolution

$\boldsymbol{B}(t)_{11hr}$

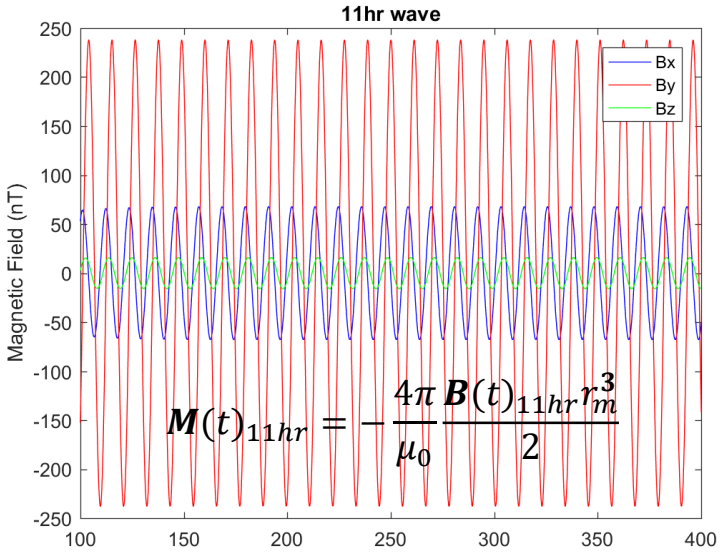


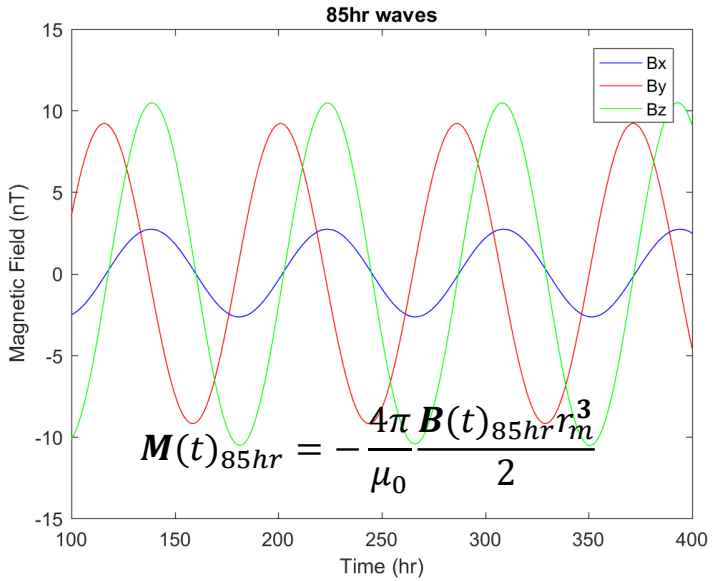


convolution

$\boldsymbol{B}(t)$

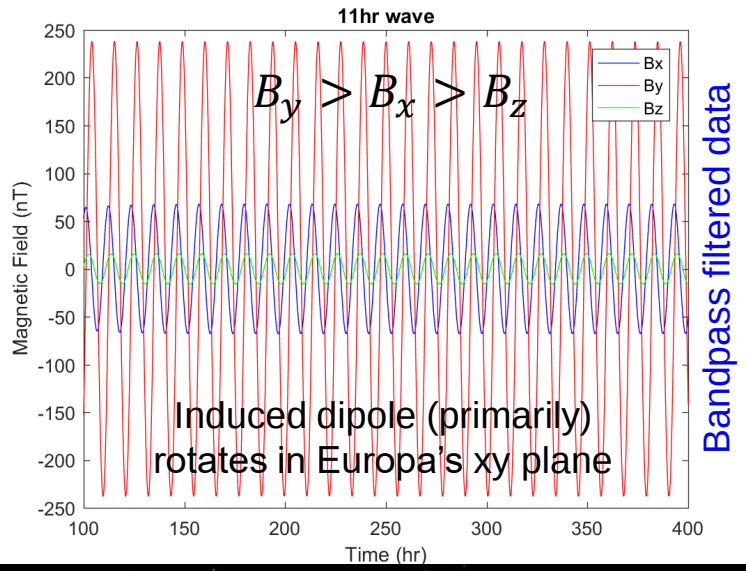
$\boldsymbol{B}(t)_{85hr}$

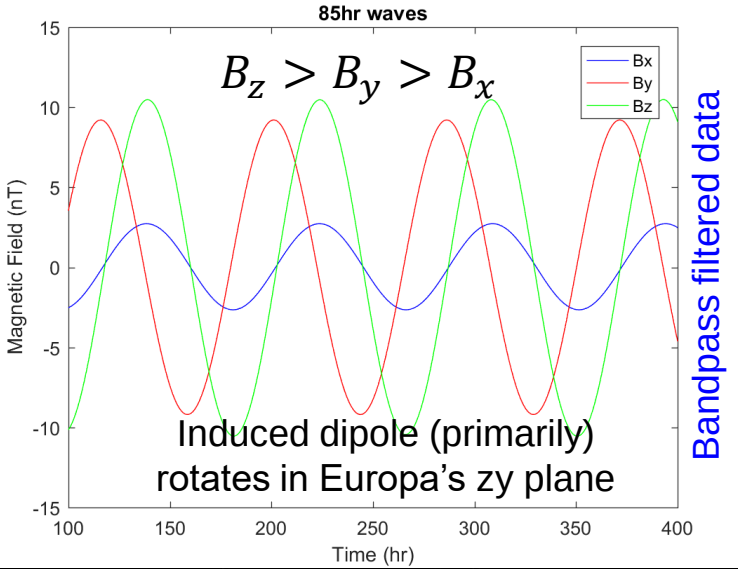


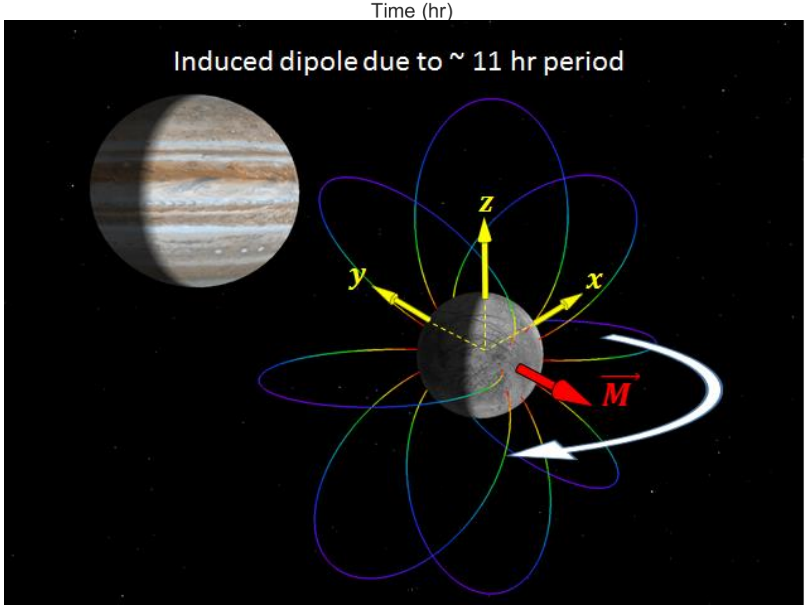


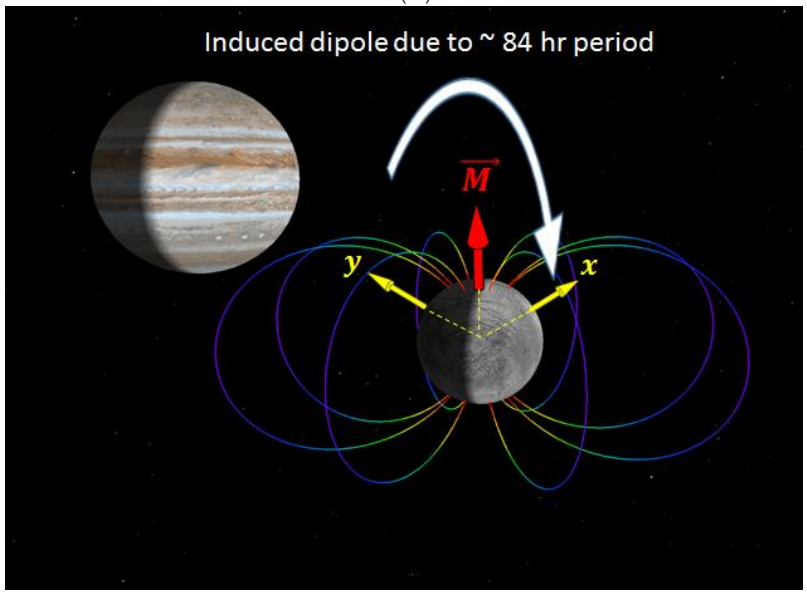
Note that filtering is done as a post processing step because there are non-negligible phase delays associated with digital filtering.

Orientation of Induced Magnetic Dipoles









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MATLAB: Simulation Description

- Matlab environment …
  - Mice (SPICE toolkit) provides very simple interface to acquire complex geometry
  - very easy to implement signal processing routines on post processed data in order to acquire the 11 hour and 85 hour induced dipoles

- Currently am only simulating the bodies of Europa and Jupiter.
  - This allows for a significant reduction in computation time compared to STK.

Preprocessing steps: *for each iteration …*

1. Call cspice_spkpos: get position of Europa relative to Jupiter
2. Call JupiterVIP4: evaluate Jupiter's magnetic field at Europa's position
3. Call cspice_pxfor: compute matrix that transforms Jupiter frame to Europa's frame
4. Project Jupiter's magnetic field on Europa's fixed axis (IAU_Jupiter → IAU_Europa)

Postprocessing steps: *for each iteration …*

1. Filter magnetic field time series to extract 11 hour and 85 hour waves
2. Rotate user defined latitude, longitude, and altitude to time dependent magnetic equator
3. Compute and display field lines

MATLAB: Drawing Magnetic Field Lines

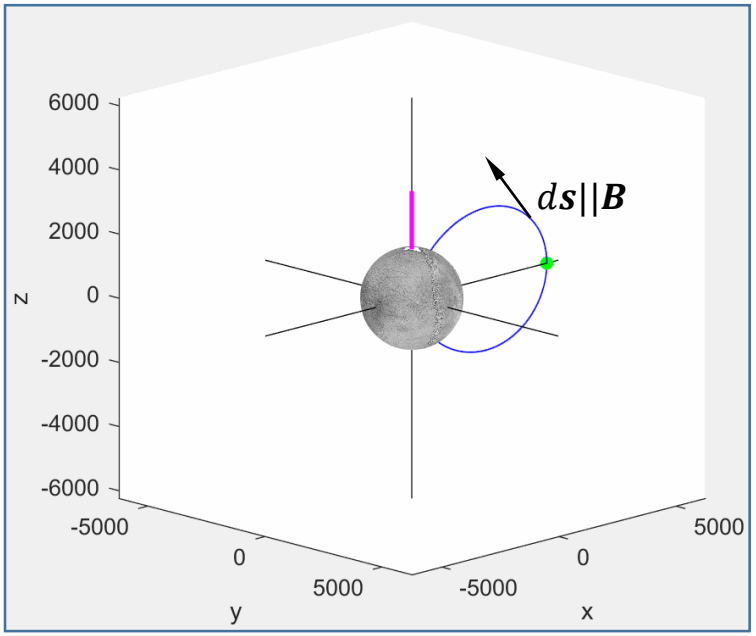
A magnetic field line represents the directionality of a magnetic field

Euler method: simplest Runge-Kutta method

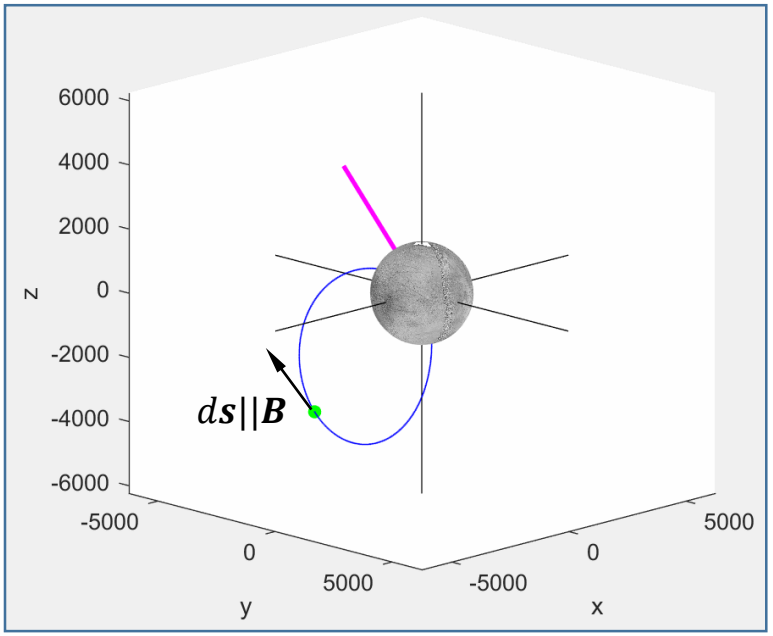
$$d\boldsymbol{s} = \hat{x}dx + \hat{y}dy + \hat{z}dz$$
$$\boldsymbol{B} = \hat{x}B_x + \hat{y}B_y + \hat{z}B_z$$

$$\boldsymbol{s}_{n+1} = \boldsymbol{s}_n \pm h\, f(\boldsymbol{s}_n)$$

$$x_{n+1} = x_n \pm h\, f(x_n) = x_n \pm h\,\frac{dx}{ds} = x_n \pm h\frac{B_x}{B}$$
$$y_{n+1} = y_n \pm h\, f(y_n) = y_n \pm h\,\frac{dy}{ds} = y_n \pm h\frac{B_y}{B}$$
$$z_{n+1} = z_n \pm h\, f(z_n) = z_n \pm h\,\frac{dz}{ds} = z_n \pm h\frac{B_z}{B}$$

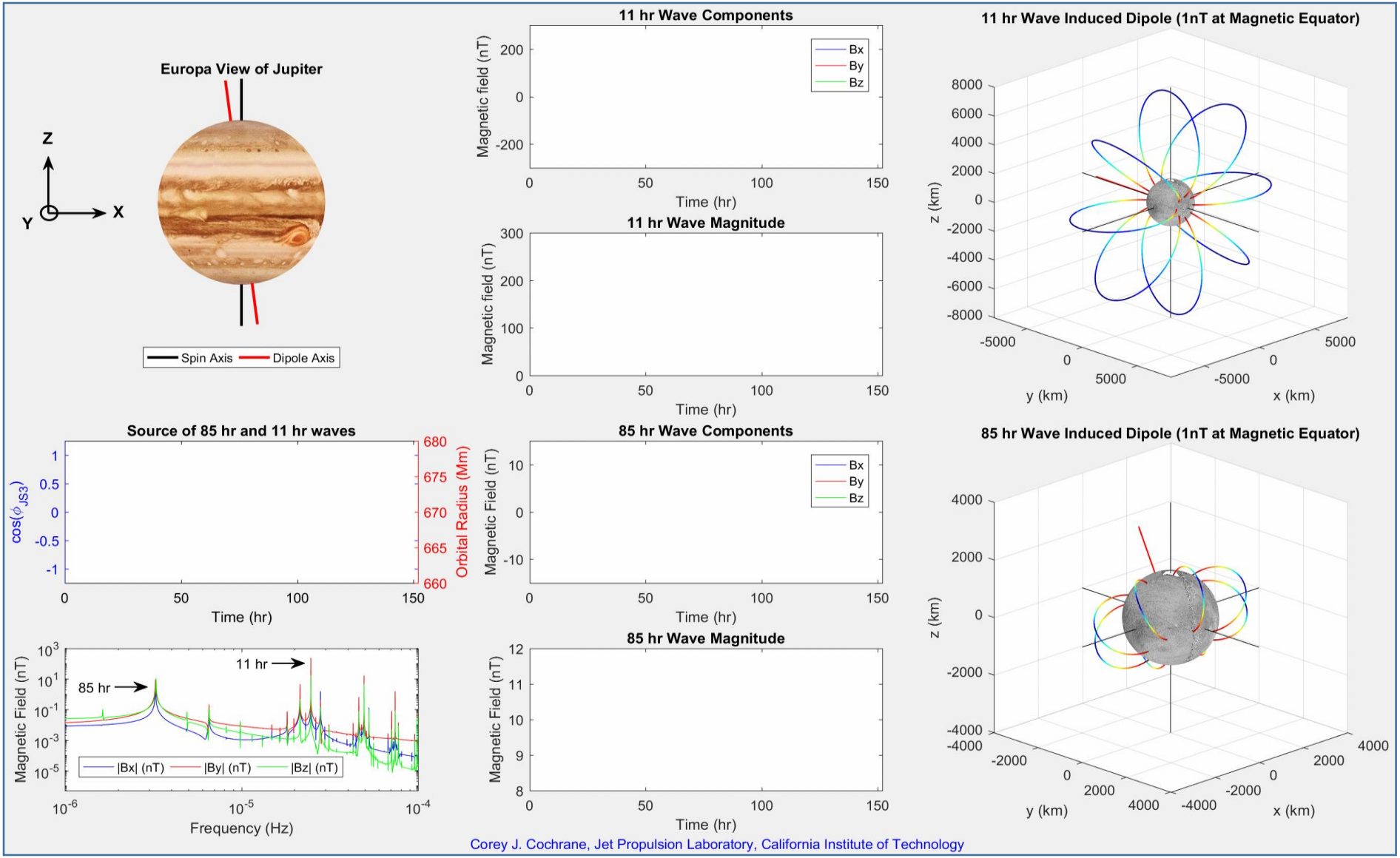


magnetic axis aligned with spin axis:
points in x y plane are sufficient to start line tracing algorithm



magnetic axis at arbitrary direction:
First start with points in xy plane, then rotate plane of points which lie on a plane perpendicular to magnetic vector

MATLAB: 11 hr and 85 hr Induced Dipoles



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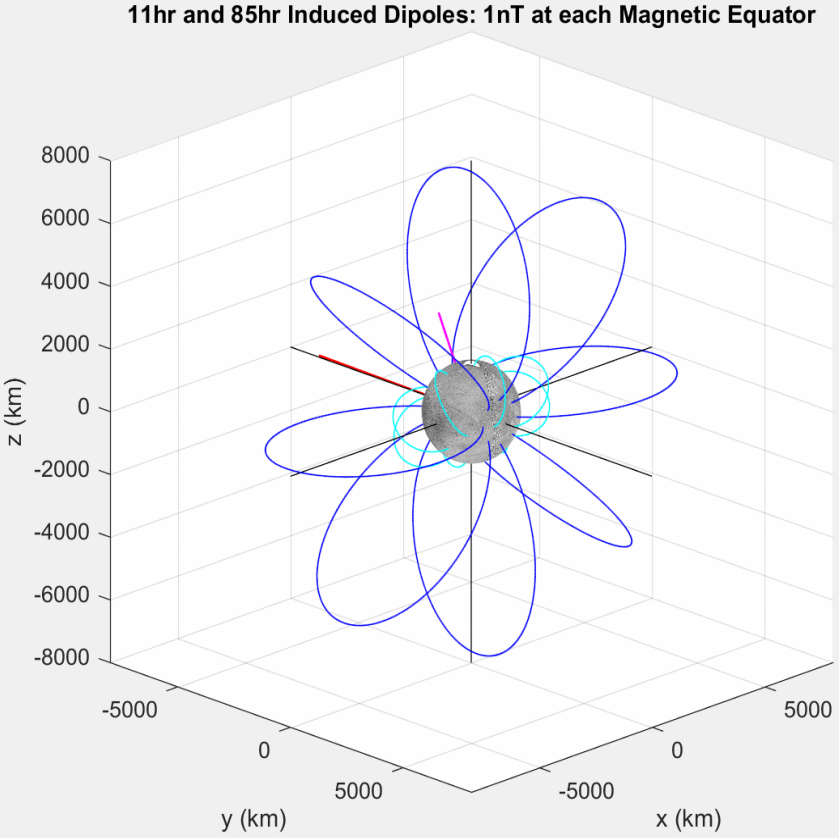
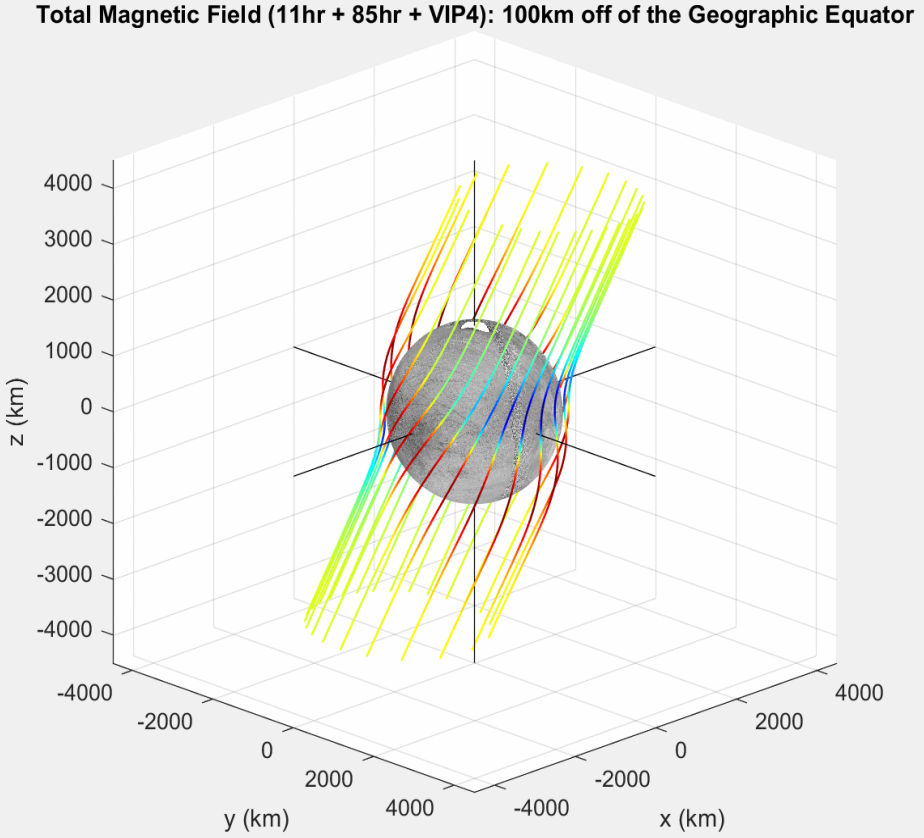
Europa Science Series – Visualizing Europa's Induced Magnetic Field

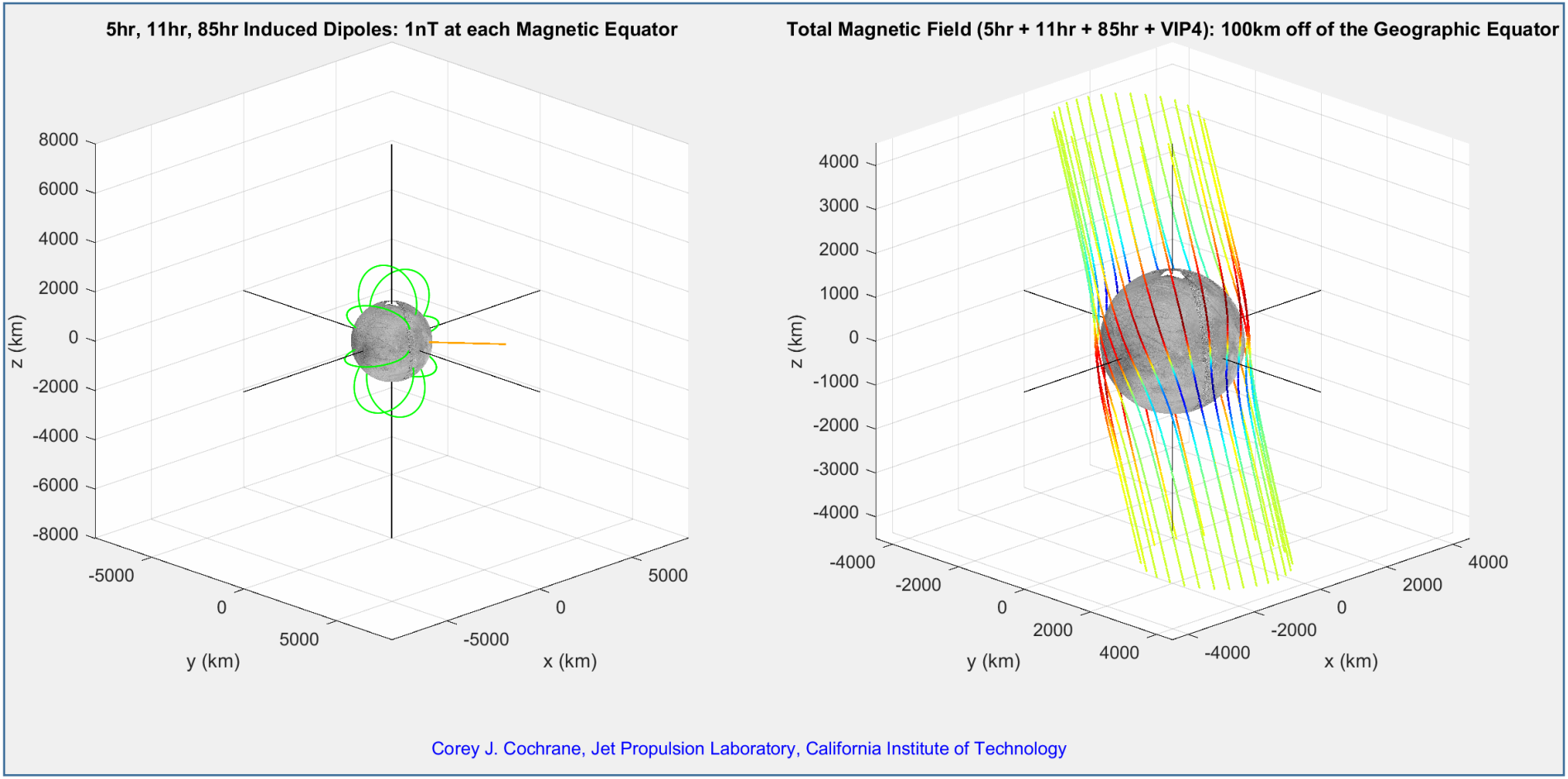
MATLAB: Europa Field Lines





Corey J. Cochrane, Jet Propulsion Laboratory, California Institute of Technology

MATLAB: Europa Field Lines



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JET/STK: Simulation Description

- Much harder to implement signal processing routines in C#/JET/STK

- Not yet familiar with how to *easily* first acquire magnetic field data, and then post process it.

- However, I was able to implement 11 hr induced dipole using the following assumption.

$$\boldsymbol{B}_{Jup,11hr} >> \boldsymbol{B}_{Jup,84hr}$$

$$\boldsymbol{B}_{Jup,11hr} \approx \boldsymbol{B}_{Jup} - \bar{\boldsymbol{B}}_{Jup} \rightarrow \boldsymbol{M}_{ind,11hr} \rightarrow \boldsymbol{B}_{ind,11hr}$$

$$\bar{B}_{x,Jup} = -0.070nT$$
$$\bar{B}_{y,Jup} = -1.040nT$$
$$\bar{B}_{z,Jup} = -409.9nT$$

- From a visualization perspective, the 11hr period suffices when visualizing the total field, because it is so dominant. Therefore …

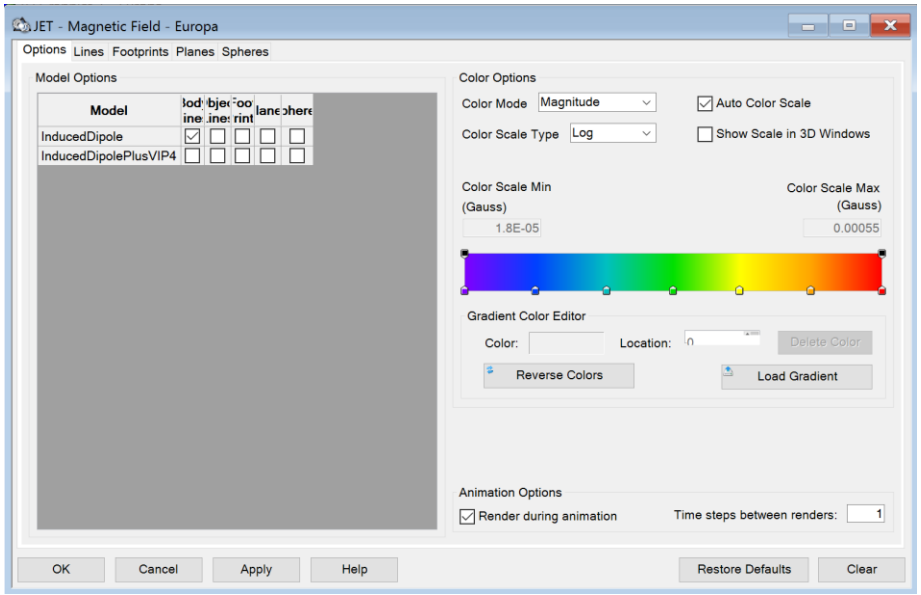
$$\boldsymbol{B}_{total} = \boldsymbol{B}_{Jup} + \boldsymbol{B}_{ind,11hr}$$

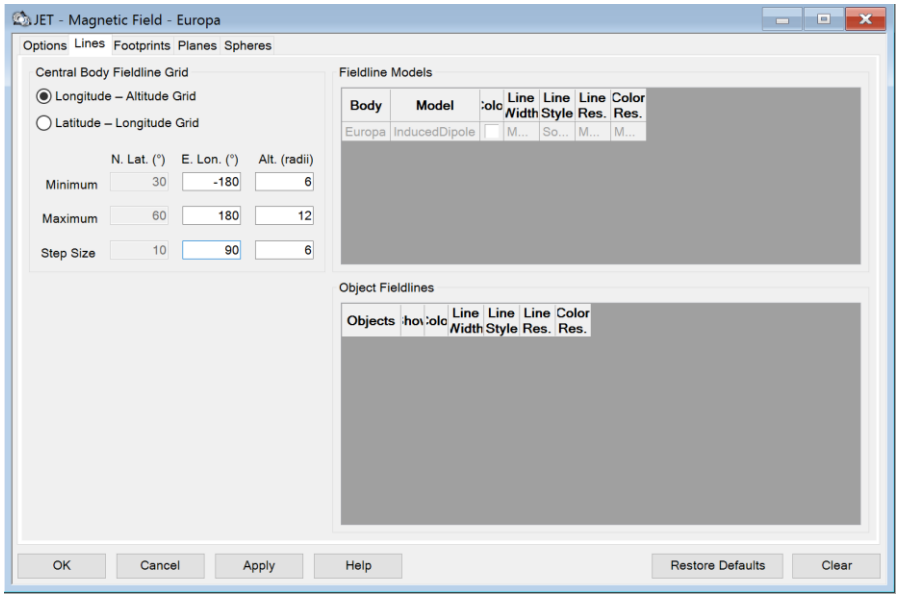
JET/STK: Graphical User Interface

- Two visualizations available:
  1. Induced dipole field lines (MagFieldInducedDipole)
  2. Induced dipole field lines plus VIP4 (MagFieldInducedDipolePlusVIP4)

- Allows for custom selection of points to evaluate the magnetic field

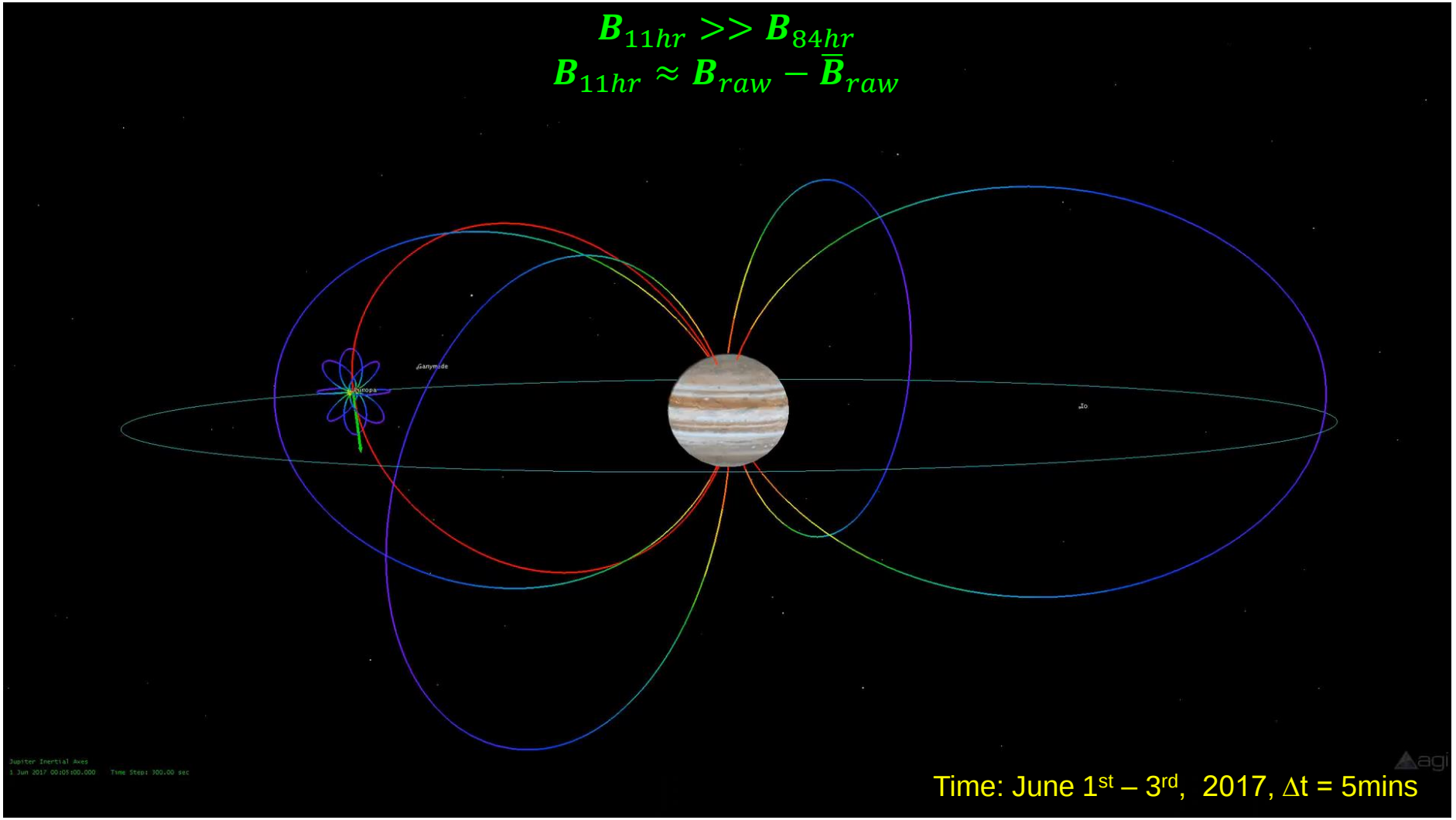
- Leverage much of the functionality that was developed previously under JET
  - Field lines, color scale linear or logarithmic
  - Object lines: magnetic field lines connected to other objects such spacecraft or other planetary bodies.





JET/STK: Simulation of 11hr Dipole

$$\boldsymbol{B}_{11hr} >> \boldsymbol{B}_{84hr}$$
$$\boldsymbol{B}_{11hr} \approx \boldsymbol{B}_{raw} - \bar{\boldsymbol{B}}_{raw}$$

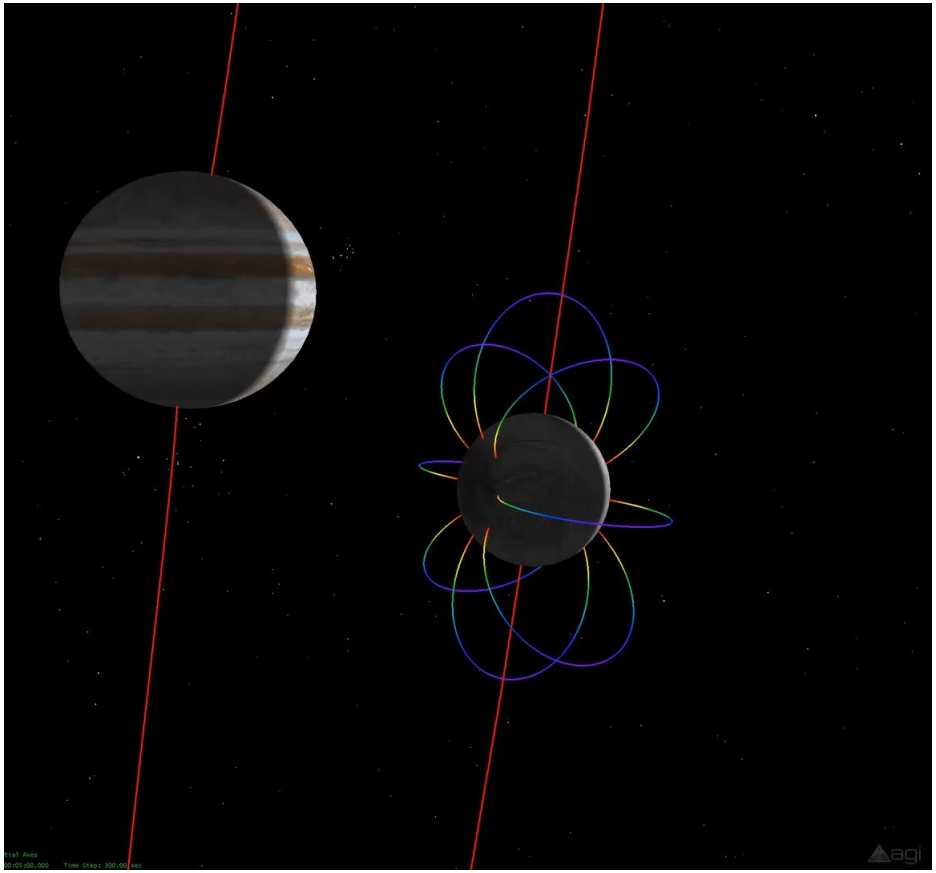


Time: June 1st – 3rd, 2017, Δt = 5mins

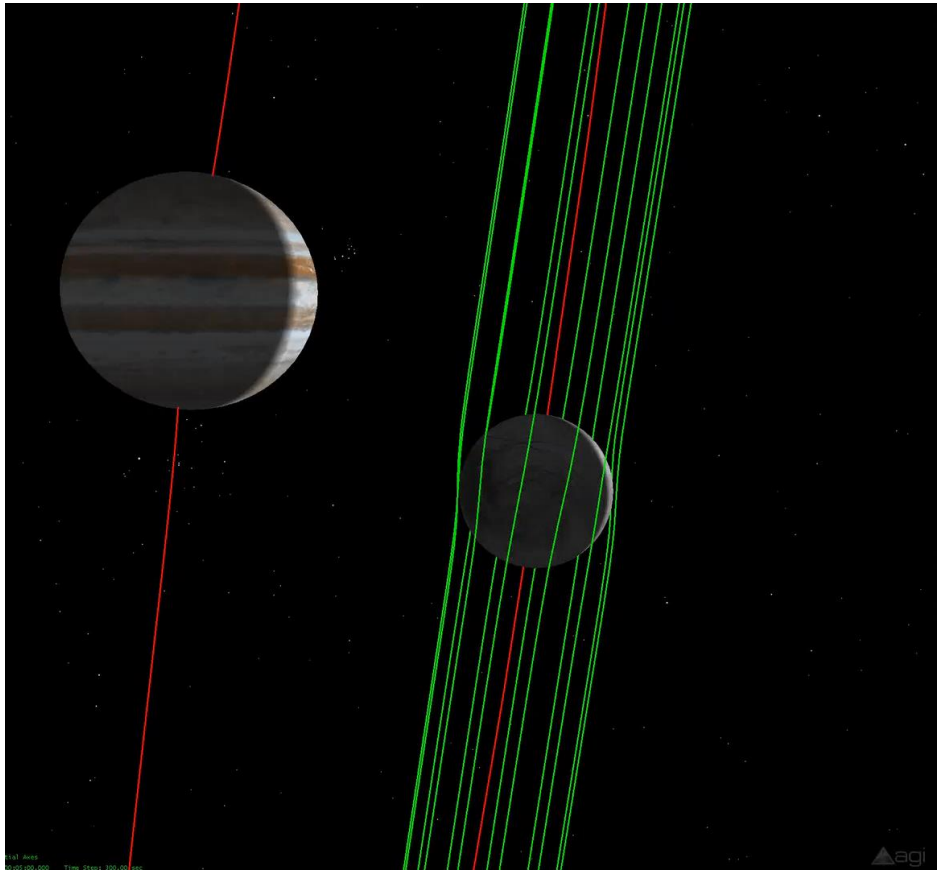
JET/STK: Simulations of Magnetic Field Lines

Again, because $\boldsymbol{B}_{11hr} >> \boldsymbol{B}_{84hr}, \boldsymbol{B}_{11hr} \approx \boldsymbol{B}_{raw} - \bar{\boldsymbol{B}}_{raw}$ for visualization purposes

Induced dipole for 11hr period



Induced dipole for 11hr period + Jupiter VIP4



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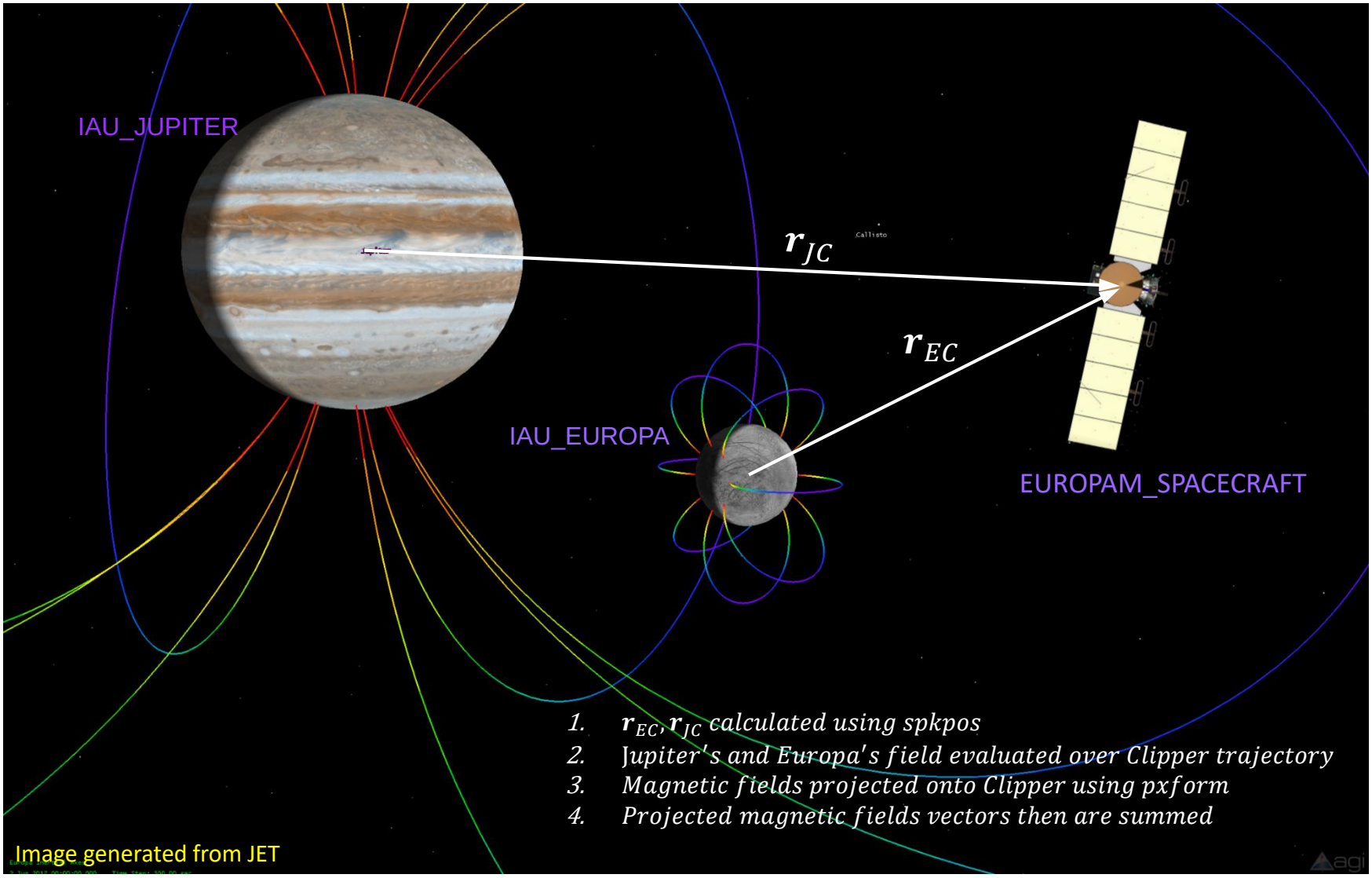
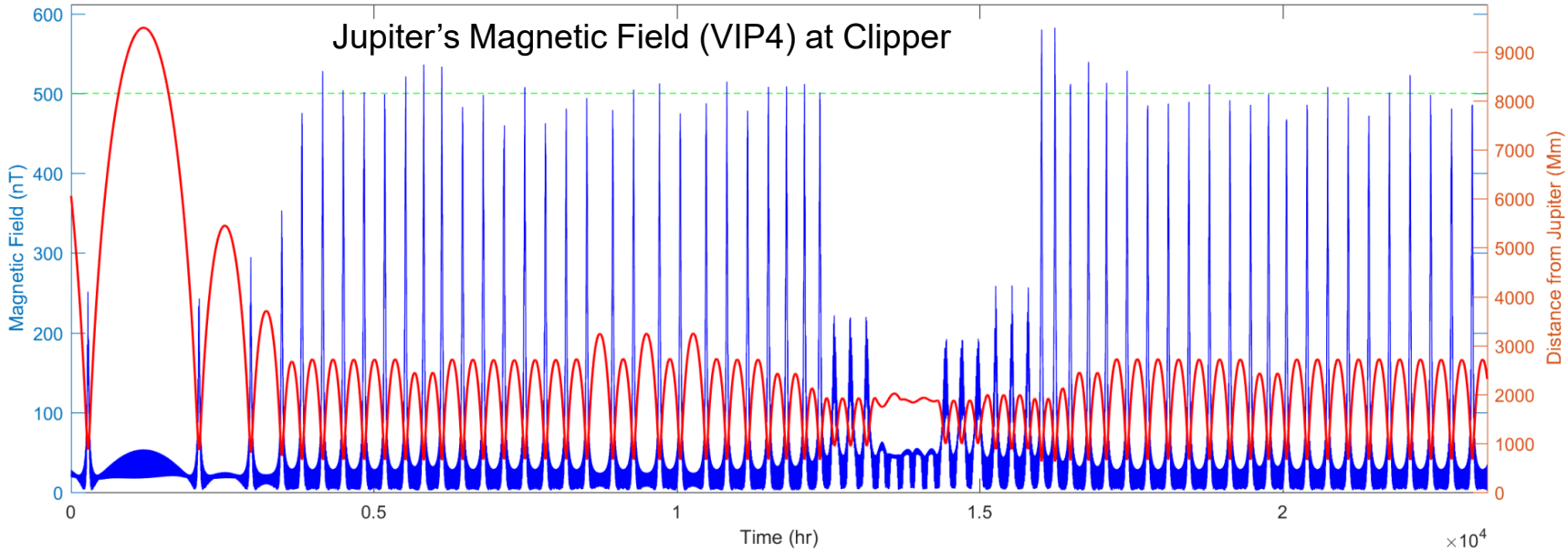
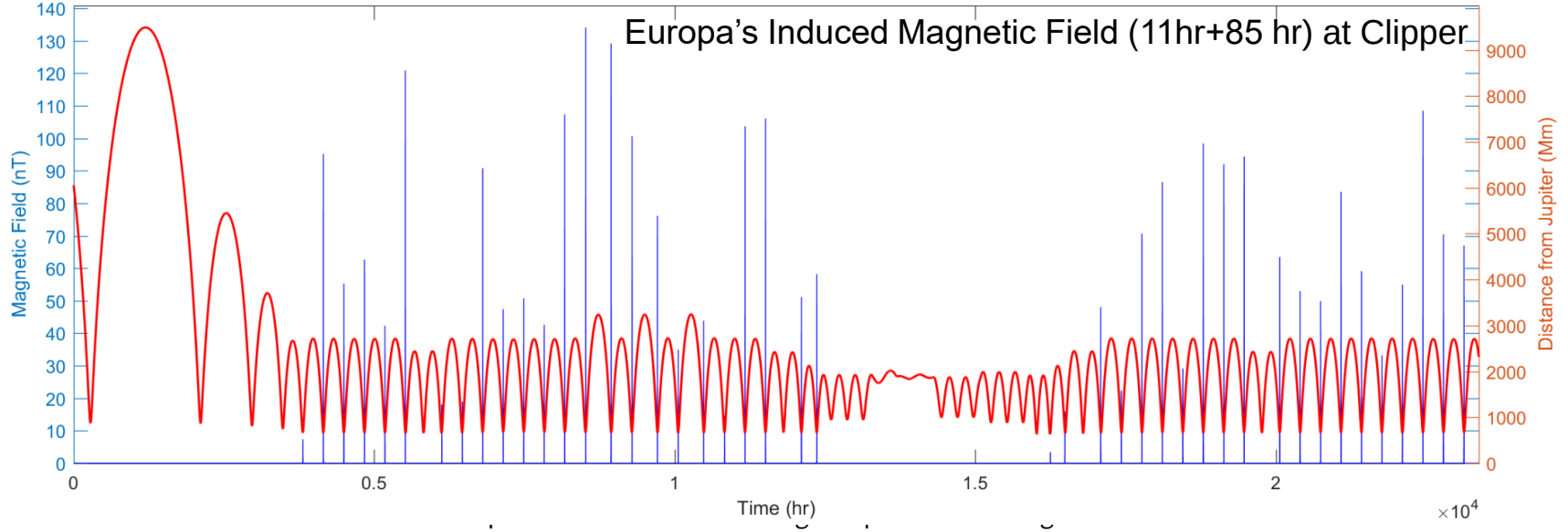
Field at Europa Clipper along 17F12v2

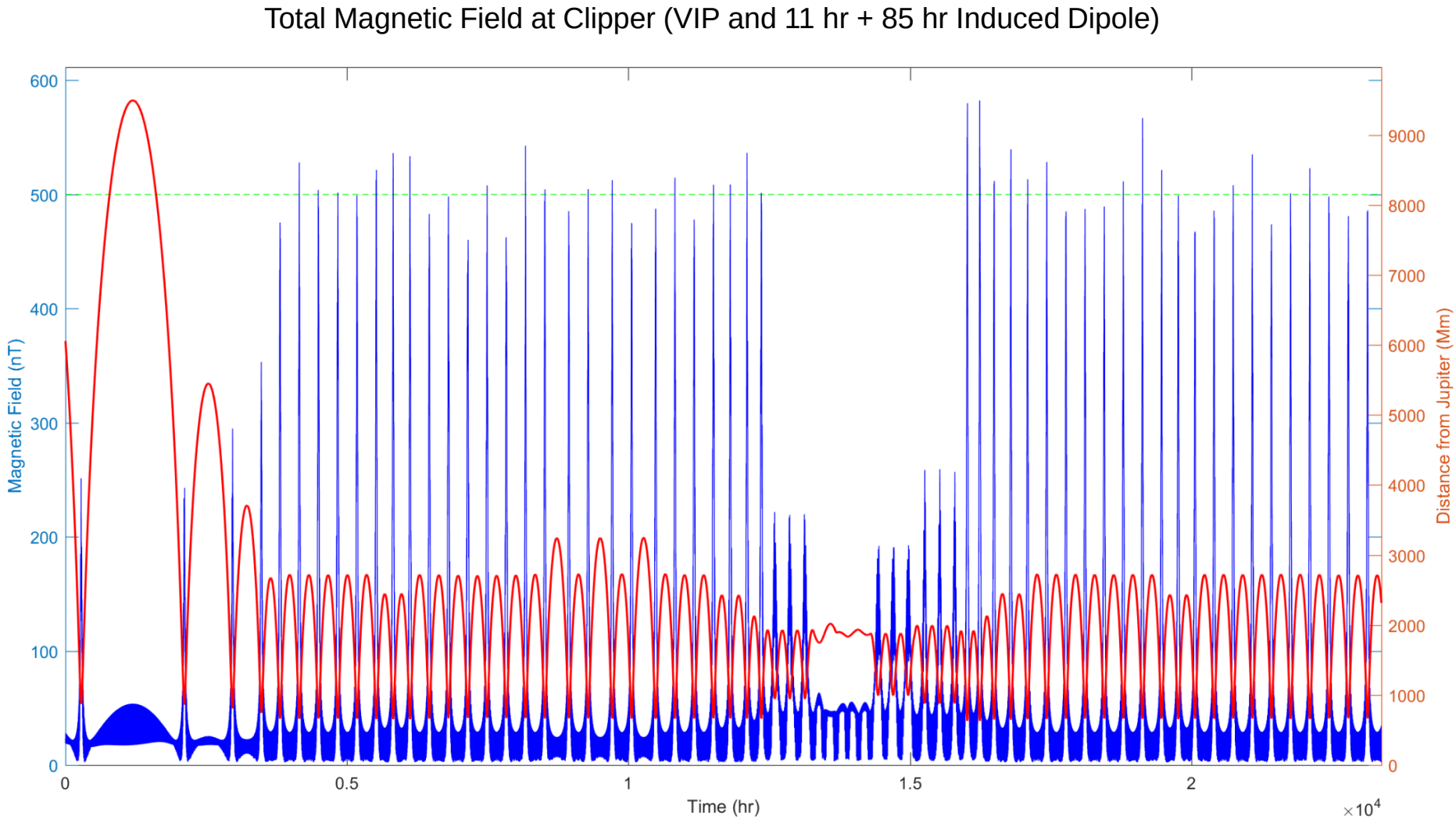


Field at Clipper along 17F12v2



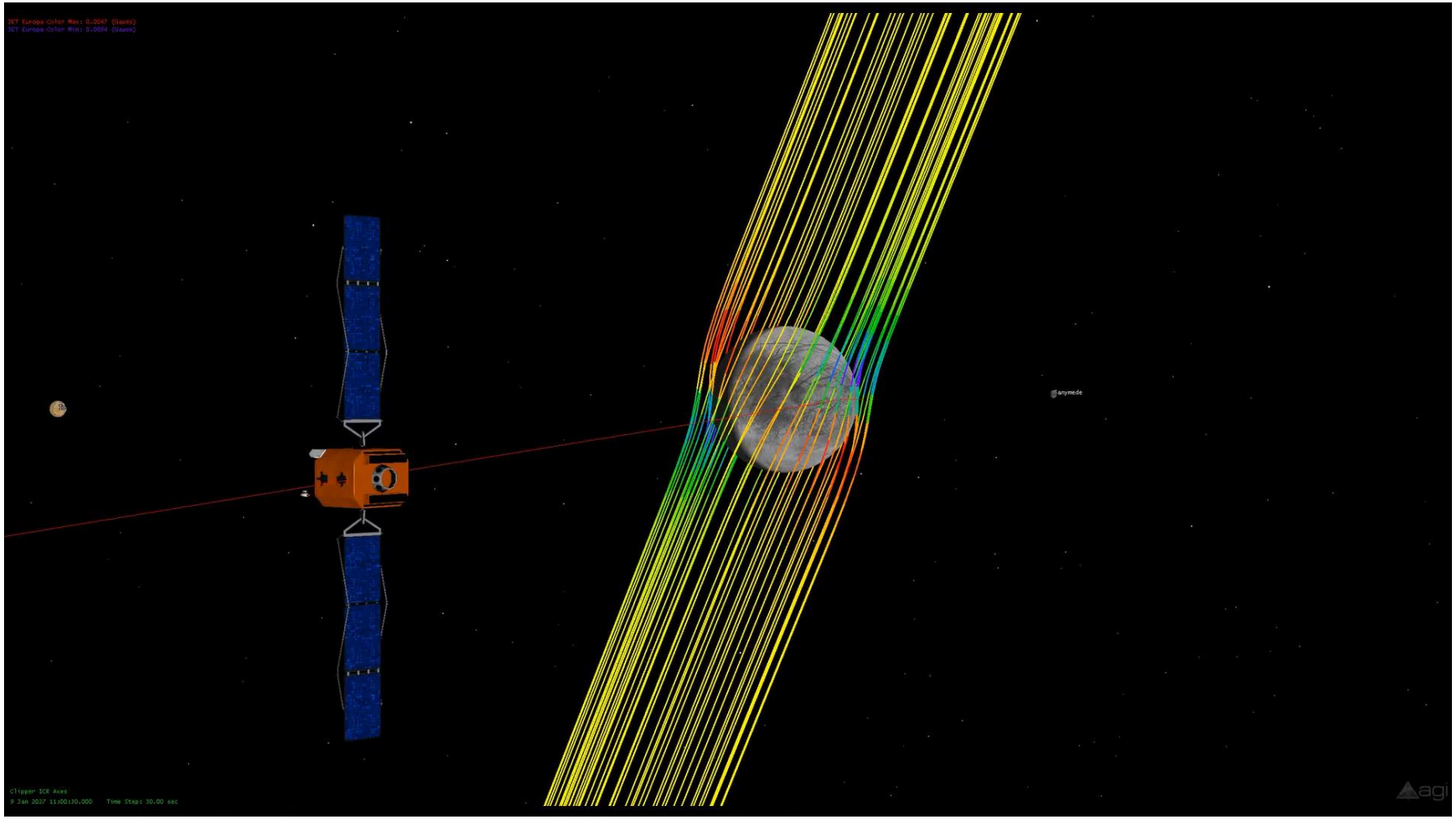


Field at Clipper along 17F12v2 (VIP4)



Clipper Flyby for 17F12v2

- Time: 4 hour flyby starting Jan 9 2027 11 UTC
- Field lines: E. longitude: 15^0 increments, Altitude: 0.01 x R_E = 15.61 km and 0.2 x R_E = 312 km



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Next Steps

JET/STK

- Implement filters generated in matlab and translate into C# for more accurately visualizing both 11hr and 85 hr dipoles.
- Develop alternative algorithms for speeding up rendering

MATLAB/SPICE

- Implement filters for other frequencies (higher order harmonics of the 11 hour and 85 hour waves)
- Possibly discuss with NAIF to have developed in Cosmographia visualization software
  - Cosmographia can be installed on all OS's and is free from the NAIF website
  - https://naif.jpl.nasa.gov/naif/cosmographia.html

Questions?

Acknowledgements

Erick Sturm (JPL) for help with JET/STK

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